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FIELD DATA FOR THE STRUCTURAL DESIGN OF COAL BUNKERS

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STRUCTURAL DIVISION

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FIELD DATA FOR THE STRUCTURAL DESIGN OF COAL BUNKERS

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Three questions arose during the design of a set of coal bunkers for a new high pressure steam power plant now under construction at Marshalltown, Iowa.

The questions are:

1. How much are the stresses and deflections of the stiffeners?
2. How much are the stresses in the bunker plates?
3. As a bunker is filled with coal, does this loading produce any bending in the supporting columns?

Most of these questions can be answered to a certain extent by the usual design computations, but more exact information was needed in order to improve the connection between the bunker and the building columns and to arrive at a more economical design. The dimensions and layout of the new coal bunkers happened to be very similar to those located in the Sixth Street Power Station of the Iowa Electric Light and Power Company in Cedar Rapids, Iowa. Therefore, it was possible to test the existing bunkers and apply the results directly to the Marshalltown plans.

The bunkers have a capacity of about 350 tons each. They are 22 feet square, and the bottom of the hopper is 45 feet below the top of the bunker, as shown in Fig. 1. Details of the connections of the stiffener beams are shown in Fig. 2.

Experimental Procedure

Tests were conducted on August 11, August 28, and on September 2 and 3, 1952, and the following measurements were taken:

1. Strains and deflections of one stiffener.
2. Strains in bunker plates.
3. Compressive strains in one supporting corner column.
4. Shape of coal pile in the bunker.

Such measurements have not been available heretofore. Of course, data collected in the field are apt to be less consistent than those obtained under well-controlled laboratory conditions. Therefore, field measurements are more difficult to interpret than similar laboratory data. However, measurements on an actual full-sized bunker are much more valuable to the design-engineer.

Test No. 1

The first test was performed on August 11, 1952, and lasted from 6:00 A.M. to 2:35 P.M. At the start of the test Bunker No. 3 was almost empty. A grid of reference lines had been laid out on the steel floor gratings at the top of the bunker. Then, the depth of coal remaining in the bunker was measured by plumbing with a flexible tape which was lowered from predetermined grid-points at the top of the bunker. The distances below the datum plane of the bunker top are referred to hereafter as "D-distances".

Then the coal was dumped into the bunker through a mechanical coal dumper. By careful observation, it was possible to determine the amount of coal delivered to the bunker by the conveyor belt. According to the workmen operating the conveyor belt, the coal used in these tests was from southern Illinois and is believed to have been strip-mined soft coal. The bunker was filled in four steps, as shown in Fig. 5a.

After each load increment, strains were measured by fourteen SR-4 electric strain gages, and stiffener deflections were observed at locations of gages F and G (Fig. 5a). Subsequently, "D-distances" were measured from the top of the bunker to determine the shape of the coal pile inside the bunker. Finally, all strain and deflection readings were checked, to complete one cycle of measurements.

The location of strain and deflection gages used in the tests is indicated in Figs. 5a and 11. Seven SR-4 strain gages were located on Column No. 3, in a horizontal plane, 18 inches below the Bend Line: four SR-4 gages were glued on the bunker plates, and three on the outer flange of the stiffener beams, parallel to the axis of the beam.

The instrumentation is shown in Figs. 3 and 4 and will be explained later.

A survey of the data disclosed that strains measured on Column No. 3 were highly erratic and could not be analyzed. This difficulty was traced to the selector switch connected to these gages. Therefore, it was decided to do the entire test over, using a new switch and making some other improvements in instrumentation and testing technique.

Test No. 2

Originally, a completely new test was planned for August 28, and the previous experiment was to be treated as preliminary. However, the bunker was nearly full on the morning of August 28. So, it was decided to study the bunker as coal is "unloaded" through a two-foot square gate at the bottom.

A "crater" forms when coal is being withdrawn from the bunker. "D-distances" were taken to determine the shape of this crater (Fig. 5b).

Inadvertently, a pencil fell into the bunker and landed on the coal. This gave an opportunity to observe the movement of the coal as it is withdrawn from the bunker. For a few minutes the pencil remained where it had landed, then it rolled downhill four or five feet. A little later it rolled downhill some more, reaching the bottom of the "crater" after about 20 to 30 minutes. Subsequently, the pencil disappeared from sight. The path of the pencil can be regarded as representing the movement of the coal, and it is approximated by the dotted line in Fig. 5b.

Test No. 3

A complete test was made on September 2 and 3, following the procedure developed in previous tests.

One important difference between this test and that of August 11 is the fact that the bunker was not completely empty at the start of the test. As a matter of fact, coal was piled against the side where the instruments were attached. This condition is illustrated in Fig. 5c, which shows cross-sections at successive stages of the test.

Also, in contrast to Test No. 1, during this test coal was being withdrawn from Bunker No. 3. The amount of coal used was checked at various intervals.

All tests were carried out without interfering with the normal operation of the power plant. Of course, the data were observed and recorded as carefully as possible, and it is believed the objectives outlined above have been attained. However, to gain a complete picture of the structural behavior of a bunker, more extensive tests performed under controlled conditions are necessary.

Instrumentation

Strains were measured by means of Type A-11 SR-4 electric strain gages manufactured by the Baldwin-Lima-Hamilton Corporation.

SR-4 gages have been available since 1939. They consist of a grid of very fine wire cemented to a specially thin sheet of treated paper. Such a gage is about the size of a postage stamp and is glued on the spot where the strain is to be measured. The wire in the gage is thinner than a human hair and can hardly be seen by eye. It is usually protected by a felt pad which forms part of the gage. The present gage is the result of many years of experimentation, certain wires having been developed specifically for use in strain gages.

When a fine wire is subjected to stresses, its electrical resistance is changed. This is the principle underlying the operation of the SR-4 electric strain gage. Of course, the changes in resistance are very small, and sensitive electrical instruments are required to measure it.

For additional information regarding the SR-4 gage and its accessories, the reader is referred to: An Introduction to Experimental Stress Analysis by G. H. Lee (John Wiley & Sons, 1950), and Handbook of Experimental Stress Analysis, edited by M. Hetenyi (John Wiley & Sons, 1950).

Deflections were measured by means of Ames dial gages as illustrated by Fig. 4. Dial gages are also described in the references given above.

Computation of Coal Pressures

The pressure exerted by a granular material on the vertical and inclined walls of a deep circular bin can be computed by Janssen's Formula. This formula has been adapted to the design of coal bunkers in a recent paper, "Design of Large Coal Bunkers," by Paul Rogers, Trans. ASCE, v. 117, p. 579, (1952).

Janssen's Formula gives the coal pressure as a function of coal depth, unit weight of coal, friction angle, and the cross-sectional dimensions of the bunker. The unit weight is 50 lbs. per cu. ft. and the friction angle is 35°, as has been verified by the present tests.

After the pressure distribution has been found, the bending moment diagram for the stiffener can be drawn, as has been done in Fig. 7. The stresses can be computed from the bending moments in Fig. 7.

Stresses in Stiffeners

Stresses obtained from strains measured in Test No. 1 are listed in Table I and are compared with "computed stresses" which were computed by three separate methods.

In Method A, the stiffeners were regarded as simply supported beams and the section modulus of the I-beam section was used to compute the bending stresses. The loads were calculated by Janssen's Formula, as has been mentioned. Method A follows the practice most generally used in the design office.

In Method B, points of inflection were assumed at suitable locations as indicated on the moment diagram shown in Fig. 7. Instead of using the section modulus of the I-beam only, stresses were computed for a composite section which includes bunker plate and Gunite lining. Detailed calculations are not included here, but stresses and deflections check the measured values much better than for Method A.

Method C presents a further refinement. The tension caused by friction forces between the coal and the bunker walls is added to the bending stresses computed by Method B.

TABLE I

COMPARISON OF MEASURED AND COMPUTED STRESSES IN STIFFENER FOR 5TH STAGE, TEST NO. 1

Location	Measured* Stress psi	Computed Stress - psi		
		Method A	Method B	Method C
Gage E	2,300	5,400	2,600	2,600
Bend Line	-----	0	-5,550	-4,050
Gage F	6,300	10,900	4,400	5,900
Gage G	6,250	11,500	4,700	6,200
Maximum tensile fiber stress in vertical stiffener		11,800	5,200	6,700

*Measured stress = E:C = 30,000,000 (measured strain)

Fig. 8 shows deflection curves of the vertical stiffener at various stages of Test No. 3. These curves indicate some restraints at the ends of the vertical stiffener. From Fig. 8 the maximum deflection is approximately 15 per cent higher than the deflection registered by dial D-2. By applying this 15 per cent increase to the data of Fig. 10, the maximum deflection caused by the coal is then found to be 0.185 inches (or 1/1880 of the 29-foot span).

Measured stiffener strains are plotted as a function of the coal depth in Fig. 9. Fig. 10 shows deflections. In these two graphs the term "coal depth" used to designate the ordinates refers to "D-distances" as measured from an arbitrary point near one of the center-stiffeners on the grid laid out at the

top of the bunker. The shape of the "loading" curve in Fig. 10 is in very good agreement with the strains for gages F and G in Fig. 9. These graphs demonstrate the complexity of stiffener action. The maximum tensile stress occurs near the center of the vertical stiffener when the bunker is completely full and amounts to 6,700 psi.

Stresses in Bunker Plates

The strains in the bunker plates were measured by four gages which were placed in a location where the stress should be near the maximum. From these measurements, it was concluded that the stress in the plates does not exceed 3,000 psi.

Compressive Strains in Column No. 3

Compressive strains in Column No. 3, as measured 18 inches below the Bend Line, were recorded in Test No. 3 only and varied considerably at successive stages of the test. A typical distribution of the strains based on stages 1 to 4 of Test No. 3 is shown in Fig. 11.

The data are not sufficient to draw definite conclusions with regard to the magnitude of bending moments in Column No. 3. However, it may be noted that the average strain (as computed from strains at the four corners of the column) is in excellent agreement with the average compressive stress computed from the load. The compressive load on Column No. 3 is 27 per cent of the weight of coal loaded into the bunker. This was determined by statics and does not take into account the effect of the adjacent bunker and other secondary restraints.

Furthermore, the average compressive stress was always less than 3,000 psi. The average strains in the left flange (Fig. 11), adjacent to the coal bunker, are higher than in the right flange, as expected. The maximum strain recorded during the entire test corresponds to a stress of 5,700 psi.

At first it was thought that the stresses in the column would be of the form

$$S = \frac{P}{A} + \frac{M_x}{I_x} y + \frac{M_y}{I_y} x$$

but it does not seem possible to estimate M_x and M_y from the present strain data. This might be attributed to misalignment of the column. Imperfections in the column, initial stresses, or a combination of these.

Angle of Repose of Coal

The cross-sections (Fig. 5) and the contours (Fig. 6) indicate that the angle of repose of the coal used in these tests varies from 35° to 41° for "loading" and from 27° to 37° for "unloading", the average being 35°. These values are for strip-mined coal from Southern Illinois and are in good agreement with values given by Ketchum in "Design of Walls, Bins and Grain Elevators," McGraw-Hill Book Co., Second Edition, p. 216, 1911. The value of the friction angle in the coal pressure formulas is the same as the angle of repose.

Tests are Economical

Since the testing equipment was provided by the State University of Iowa, the total expenditures connected with these tests were less than $100. It is

expected that savings of at least $2,000 per bunker can be realized as a result of these tests.

H. R. Green and Company of Cedar Rapids, Iowa, are engineers for the Marshalltown plant and encouraged the writers to carry out these tests. A more detailed report describing this test is on file in the Engineering Societies Library.

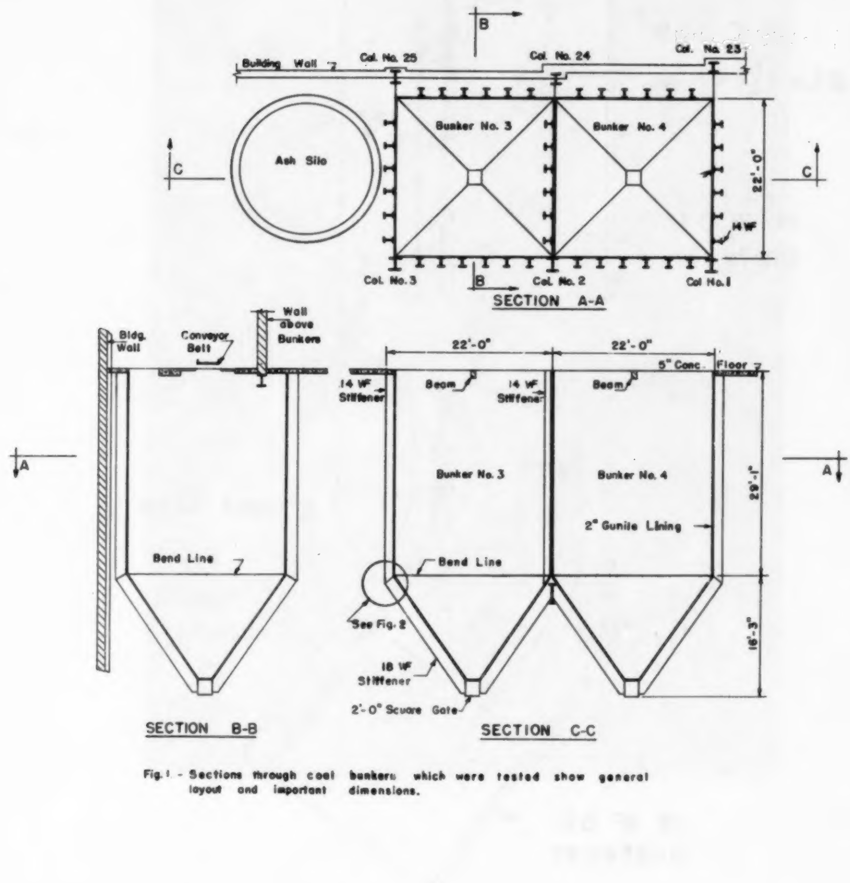

Fig. 1 - Sections through coal bunkers which were tested show general layout and important dimensions.

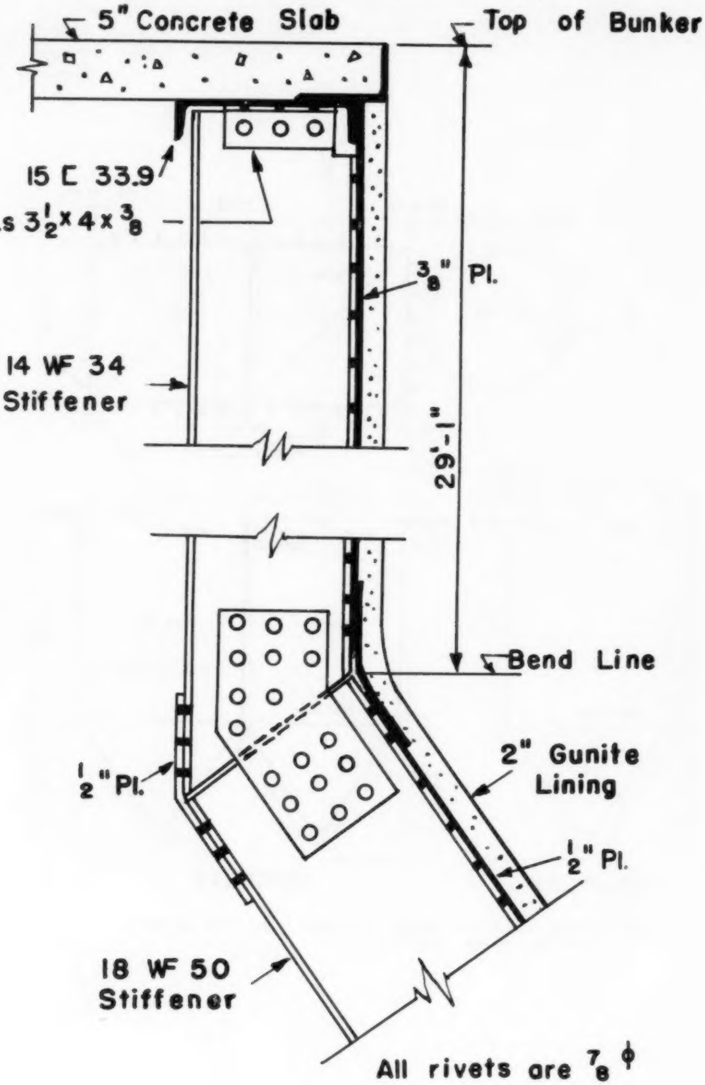

Fig. 2 - Stiffener details show connections at ends of vertical stiffener.

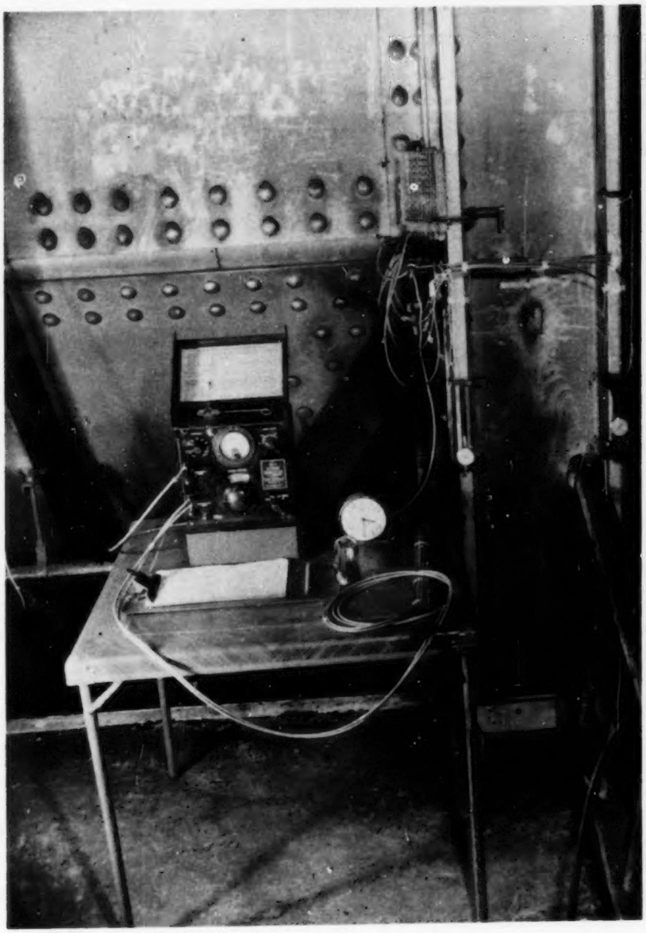

Fig. 3 - In the foreground is the SR-4 strain indicator. Electric strain gages may be seen on Column No. 3 at right.

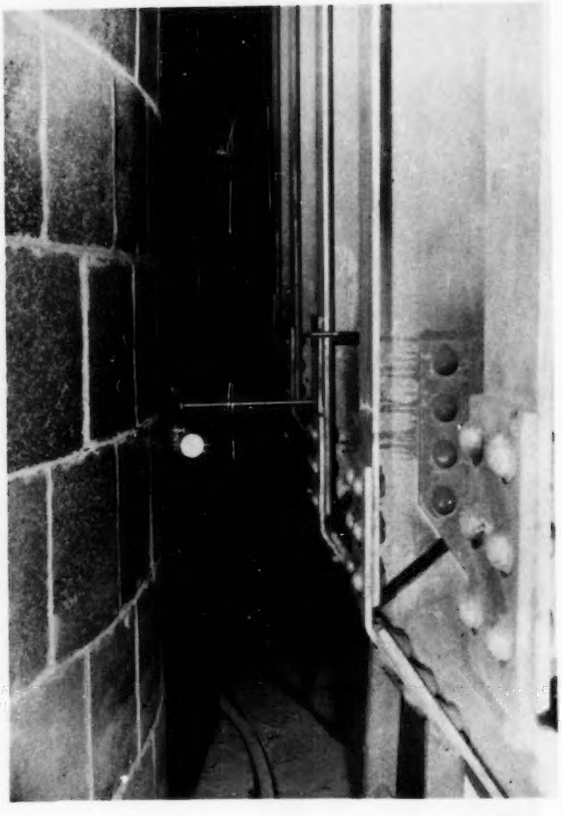

Fig. 4 - Dial gages were used to measure lateral deflection. Dial D-1 at the Bend Line is shown here. Ash Silo at left is very rigid and its deflections are negligible.

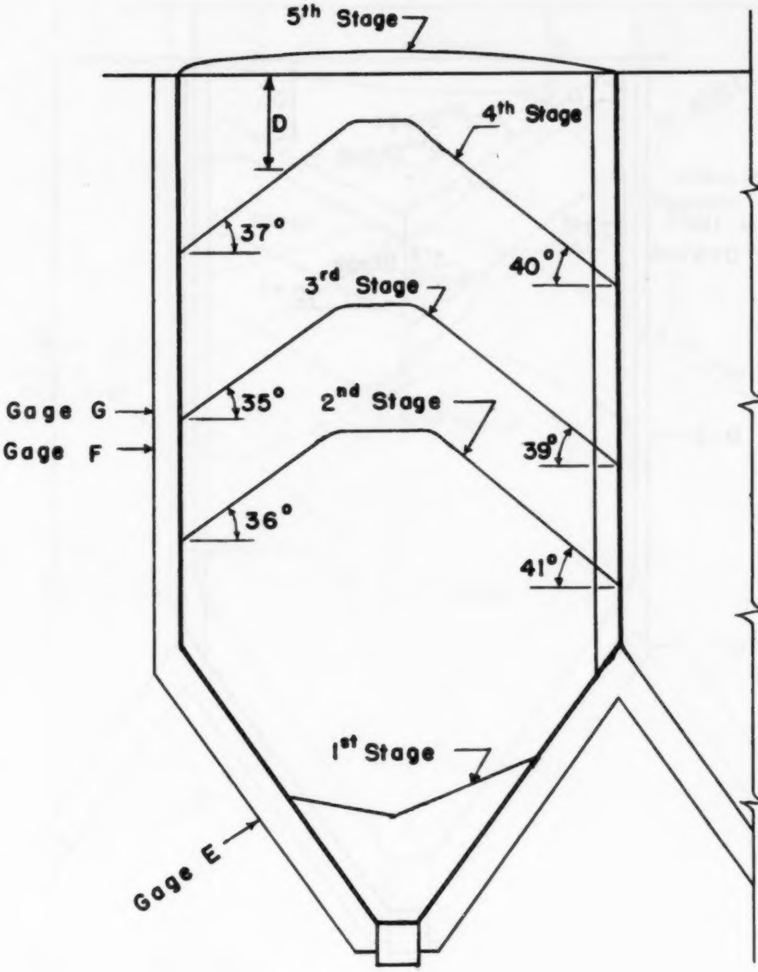

Fig. 5a - Test No. 1

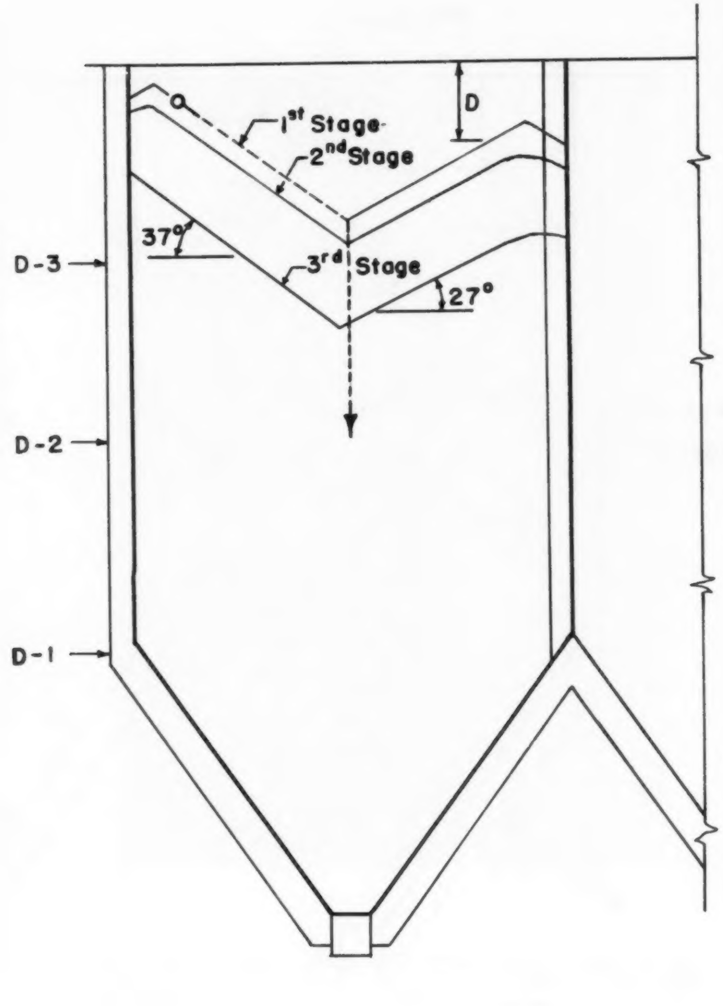

Fig. 5b - Test No. 2

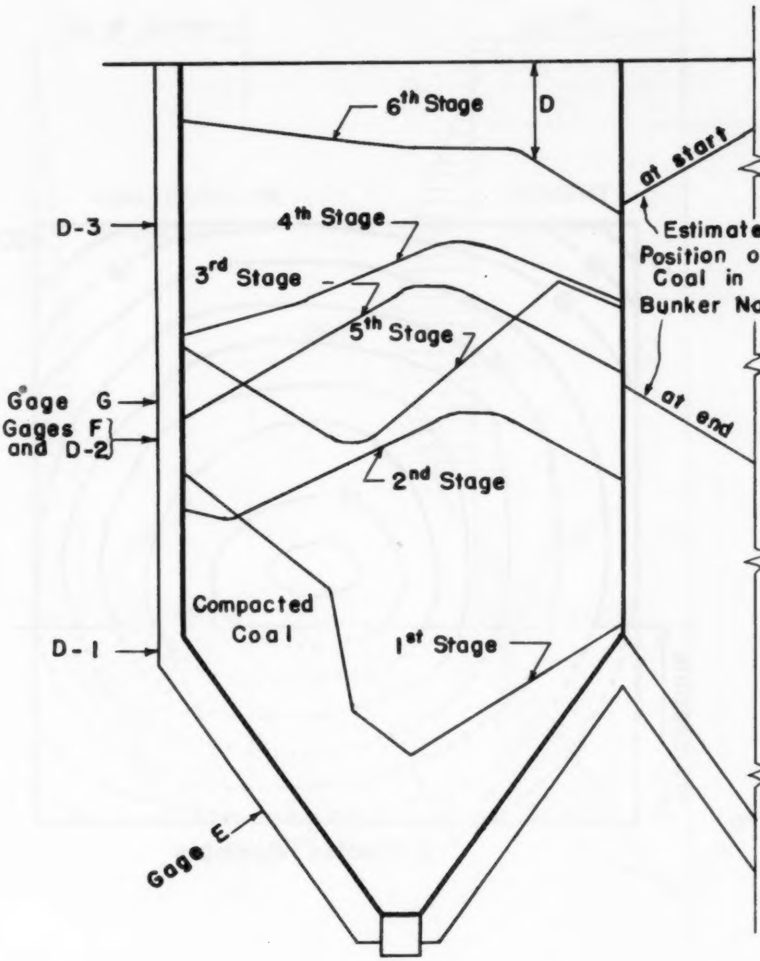

Fig. 5c - Test No. 3

Fig. 5 - Profiles of coal in bunker at various stages of Tests No. 1, 2, and 3 are shown in the sections above. These sections are oriented the same as Section C-C in Fig. 1. Location of Deflection gages is denoted by D-1, D-2, and D-3.

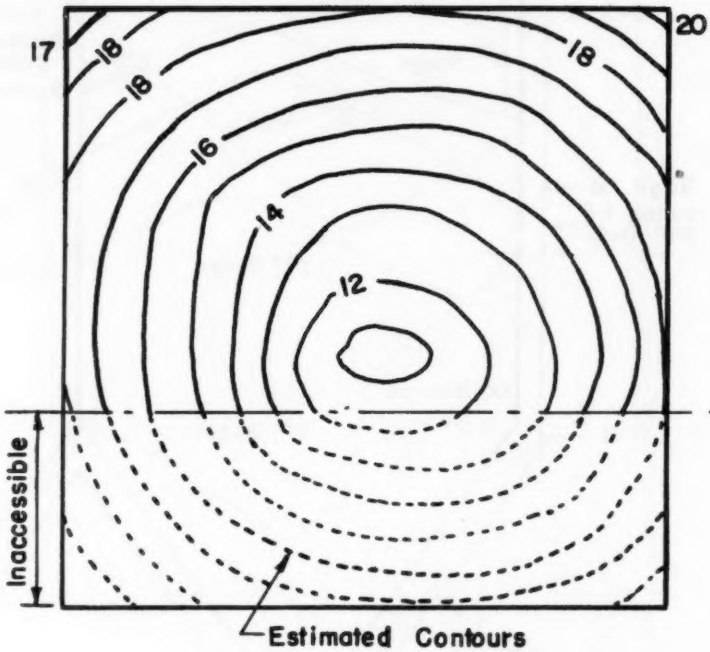

Fig. 6 - Typical contours of coal pile. This one is for 3rd stage of Test No. 3.

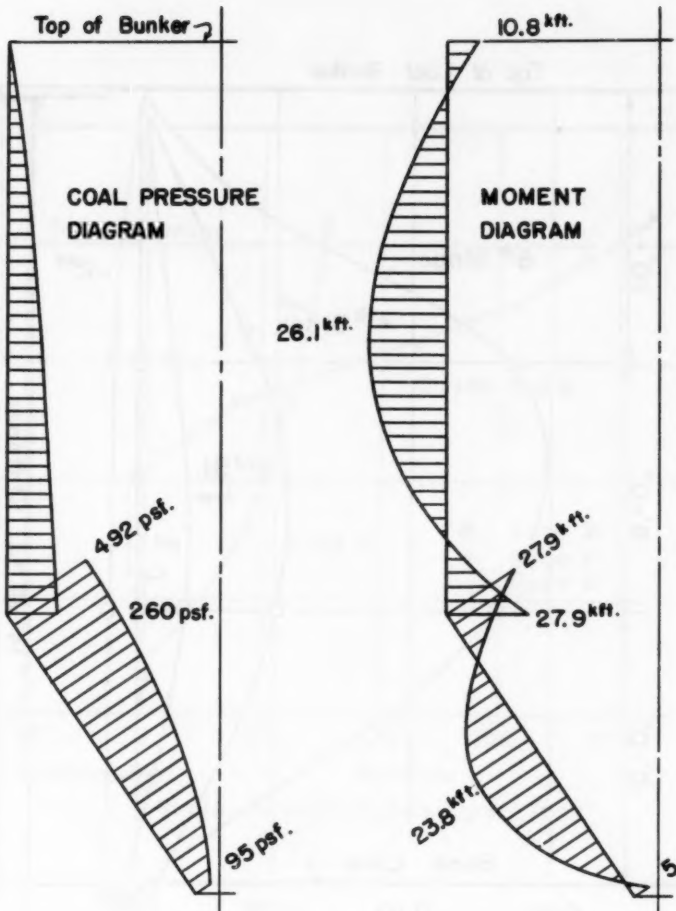

Fig. 7 - Coal pressures shown above are computed by Janssen's Formula. The moment diagram is obtained from the pressures by numerical integration. Points of inflection are assumed as suggested by the deflection curves in Fig. 8.

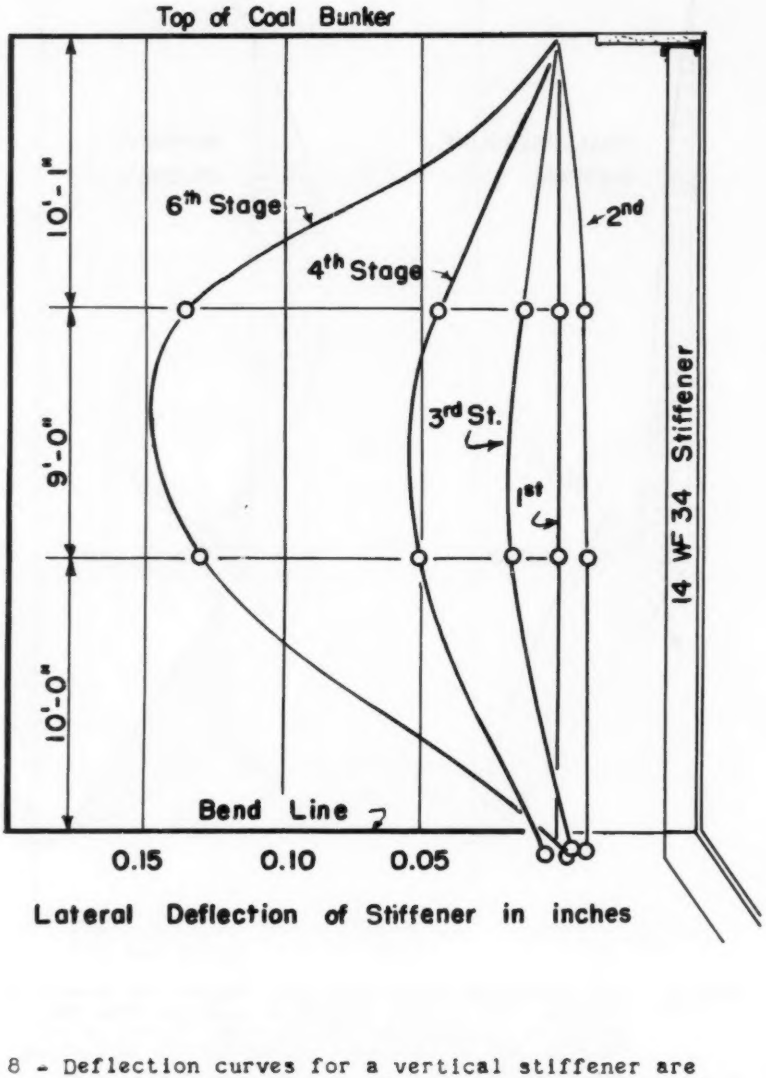

Fig. 8 - Deflection curves for a vertical stiffener are based on measurements of lateral deflections at three locations.

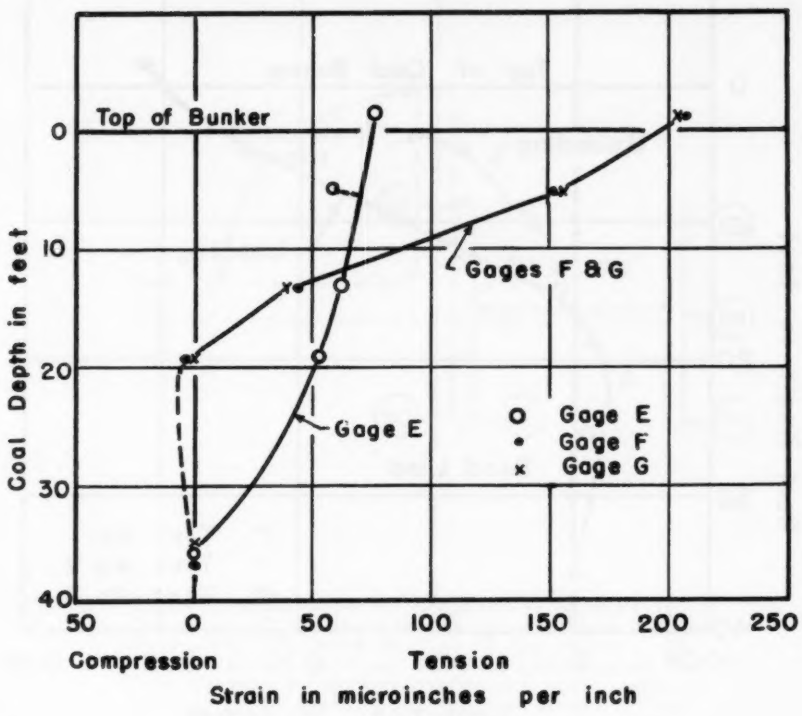

Fig. 9 - Strains in the stiffeners are not simply proportional to the weight of coal in the bunker.

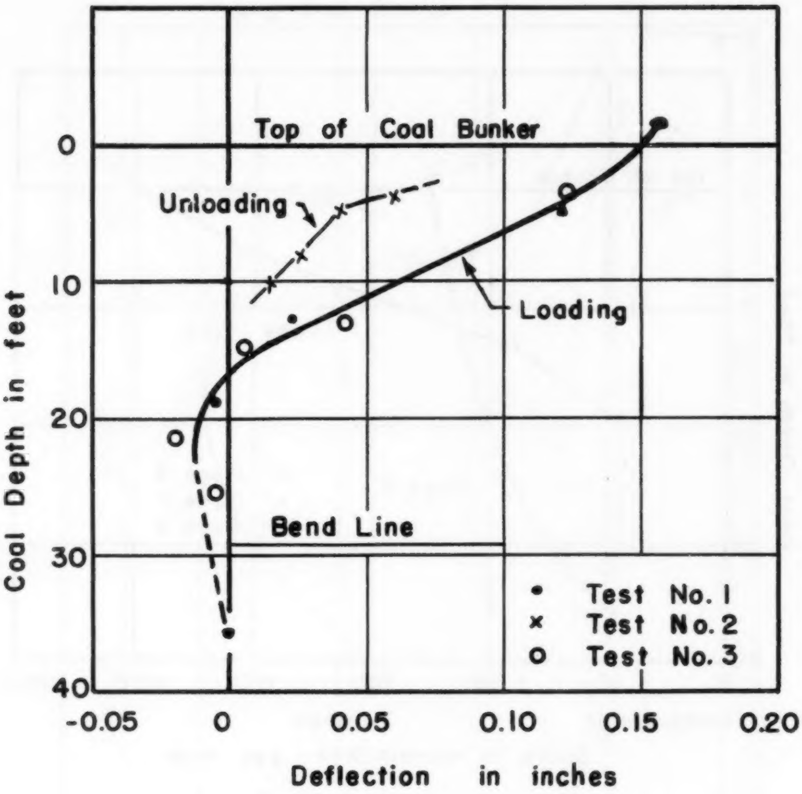

Fig. 10 - In this graph the lateral deflection at a point 10 feet above the Bend Line is plotted against coal depth. The similarity between the loading curve and the strains for gages F and G in Fig. 9 should be noted.

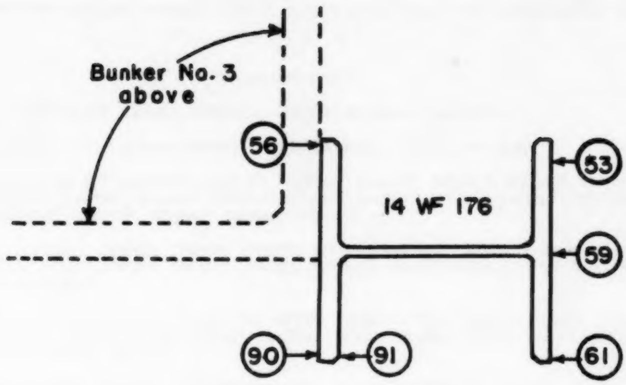

Fig. 11 - Typical distribution of compressive strains in Column No. 3, as measured 18 inches below the Bend Line, indicates bending in the column. The average strain obtained from the readings at the four corners is 65 microinches per inch, corresponding to an average compressive stress of 1950 psi. The value computed from the load is 1780 psi.

PROCEEDINGS-SEPARATES

The technical papers published in the past twelve months are presented below. Technical-division sponsorship is indicated by an abbreviation at the end of each Separate Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering" or write for a cumulative price list.

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APRIL: 428(HY)[e], 429(EM)[e], 430(ST), 431(HY), 432(HY), 433(HY), 434(ST).

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a. Beginning with "Proceedings-Separate No. 200," published in July, 1953, the papers were printed by the photo-offset method.
b. Presented at the Miami Beach (Fla.) Convention of the Society in June, 1953.
c. Presented at the New York (N.Y.) Convention of the Society in October, 1953.
d. Beginning with "Proceedings-Separate No. 290," published in October, 1953, an automatic distribution of papers was inaugurated, as outlined in "Civil Engineering," June, 1953, page 66.
e. Discussion of several papers, grouped by divisions.
f. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.

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